COMPARATIVE STUDY OF THE "RADIO–PLANETS"

André Boischot

DASOP – Observatoire de Paris–Meudon
92195 Meudon Principal Cedex, France.

Abstract

Four planets – the Earth, Jupiter, Saturn and Uranus – are known to be sources of low frequency "auroral" emissions, due to energetic electrons precipitating in regions of high latitude. These emissions might differ from planet to planet either because the emission mechanism is different, or because the source structure and energetic electron populations are different. Hence it is very interesting to compare the known characteristics of the four planetary "auroral" emissions.

In the first part, we emphasize on the difficulties of this comparative study, due mainly to the limited amount of information we have so far.

In the second part, we summarize the main properties of the planets on which the radio emission is dependent, i.e. the magnetic field and the cold and hot plasma populations in the source, around it and more generally in the planet's inner magnetosphere.

Then we present a comparative study of the four planetary emissions, using the ground observations of Jupiter, the data obtained by the Planetary Radio Astronomy experiment on the Voyager for Jupiter, Saturn and Uranus, and for the Earth the observations of several Earth orbiting satellites.

We consider successively the high frequency limit of the emissions, the total energy radiated and the source brightness temperature, the source location, emission diagram and source structure, the wave polarization, the fine structures in the emission dynamic spectra and finally the modulation by the planetary rotation.

It is shown that there are many similarities between the four planets' emissions which seems to justify the search for a common emission mechanism. On another hand one must not ignore the differences between the emissions, which reflect probably differences of physical conditions in the source and of the origin of the energetic electrons. The more striking of these differences are still unexplained.

1. Introduction

Comparative study of the radio planets has been made several times (Kaiser and Desch, 1984; Genova 1986; Genova 1987b), in particular during the first Graz Workshop on Planetary Radio Emissions (Rucker and Bauer, 1985). Since that time, the Planetary Radio Astronomy (PRA) experiment (Warwick et al., 1977) on board the Voyager 2 added a new planet, Uranus, to the family (Warwick et al., 1986). It is then interesting to review again the similarities and differences between the now known four radio planets: the Earth, Jupiter, Saturn and Uranus.

As is well known now, the two kinds of regions where radio emissions can take place in a magnetosphere are either regions where energetic electrons precipitate along magnetic lines of force, or regions with strong gradients of plasma density. We shall restrict the present study to the first case, which corresponds to what is generally called the "auroral" emissions.

Among the five planets known to have an intrinsic magnetic field, one of them, Mercury, does not have an extended magnetosphere, due to its proximity to the Sun and its small size, which result in the absence of an atmosphere; no attempt to detect its radio emissions has been made so far.

The four other planets are intense low frequency radio sources, due to energetic electrons precipitating along magnetic lines of force. These emissions are presented in Table 1 and Figure 1. They are the Auroral Kilometric Radiation (AKR) for the Earth, the decameter (DAM) and hectometer (HOM) radiations for Jupiter, Saturn's kilometric radiation (SKR) and Uranus Kilometric Radiation (UKR). They are described in a number of review papers (Carr and Desch, 1976; Carr et al., 1983; Kaiser et al., 1984; Leblanc et al., 1987).

Table 1

Planetary Auroral Emissions

Planet	Emission	Frequency range	Peak frequency
Earth	AKR (or TKR)	(10 kHz) – 750 kHz	250 kHz
Jupiter	HOM	(30 kHz) – (1 MHz)	15 MHz
	DAM	(1 MHz) – 40 MHz	
Saturn	SKR	(30 kHz) – 1.2 MHz	150 kHz
Uranus	UKR	(30 kHz) – 800 kHz	200 kHz

2. The difficulties if comparing the planets

The Jovian emission was first detected in 1955 by Burke and Franklin (1955a,b) with a ground based radio telescope, and has been extensively studied since then, from the ground and from space. The other planets must be observed from space only because their frequency ranges are below the cut–off imposed by the Earth's ionosphere.

The AKR has been recognized in 1965 (Benediktov et al., 1965) and studied by many Earth orbiting satellites. The Earth is the only planet where the characteristics of energetic particles and of the cold plasma have been determined by in situ measurements, inside the real source of emission.

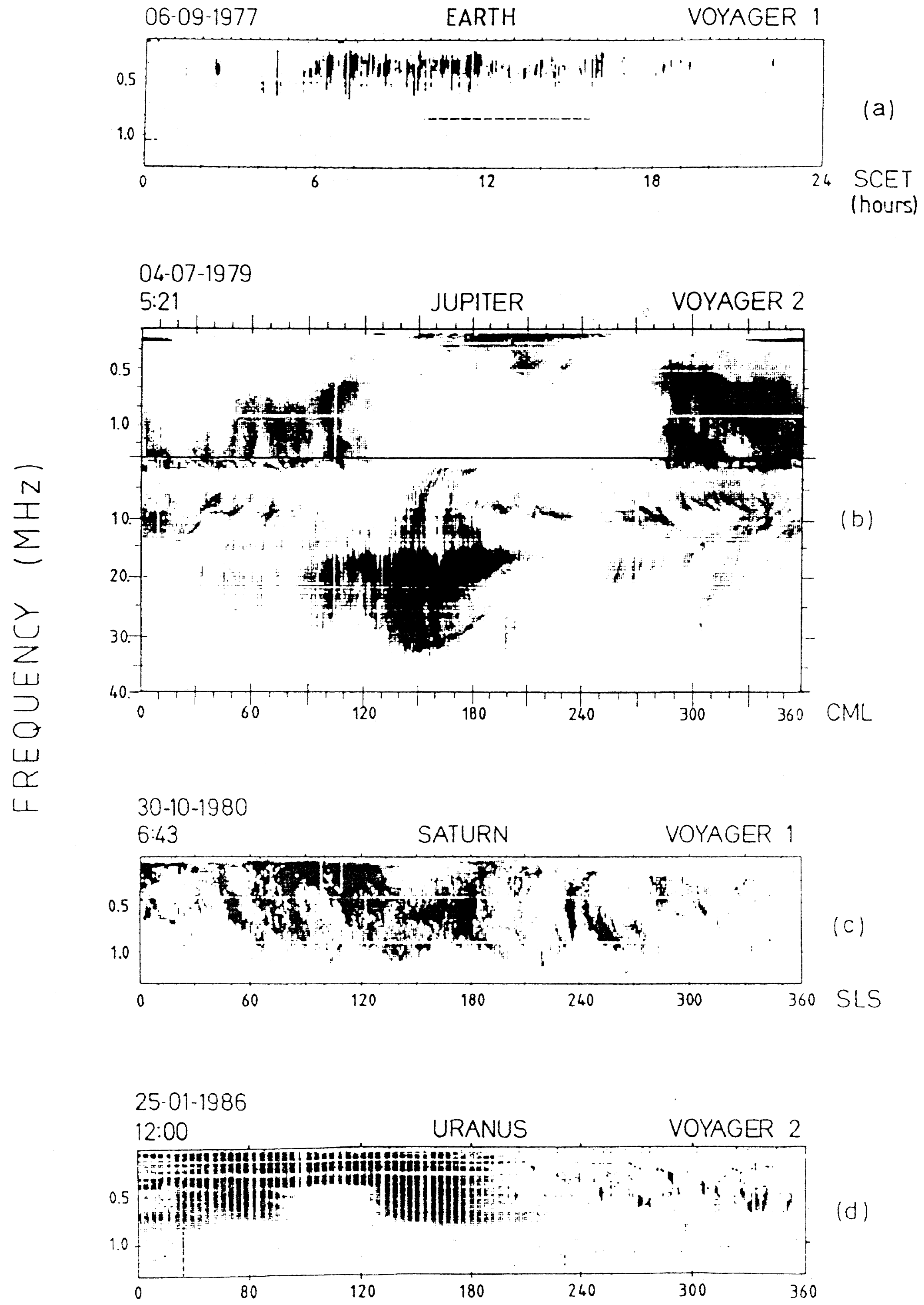

Fig. 1: Examples of dynamic spectra of auroral emissions observed by the PRA instrument. One planetary rotation is shown for the four planets.

For Saturn and Uranus, all what we know comes from the PRA experiment during two fly–bys of Saturn and only one of Uranus.

Hence, a first difficulty we shall meet in comparing the four planetary emissions is the large difference in the amount of information we have on each one.

A second difficulty is related to the geometrical coverage of these planets by our instruments. This is summarized in Figure 2. It shows the position of the sub–spacecraft point (and for Jupiter the sub–Earth point) in planetocentric local time and magnetic latitude coordinates. It can be seen immediately that the coverage is far from complete, except for the Earth.

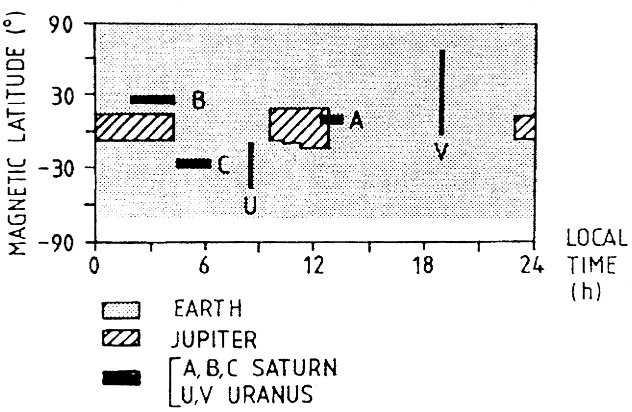

Fig. 2: Geometrical coverage, in magnetic latitude and local time, of the observations of the planets Earth, Jupiter, Saturn and Uranus (adapted from Kaiser and Desch, 1984).

It is perhaps more illustrative to present this coverage in another way. Due to the large tilt angle ($\approx 60°$) between the rotation axis of the planet and its "equivalent" magnetic dipole axis (Ness et al., 1986), and to the fact that the rotation axis lies close to the ecliptic plane, Voyager 2 explored a large range of magnetic latitudes of Uranus, about $\pm$ $60°$ (Figure 3).

Because both the precipitation of particles and the propagation of waves are primarily dependent on the magnetic field it is likely that the magnetic coordinates are the most appropriate for the study of the auroral emission.

Figure 4 is an example of the observation of UKR night side source at 480 kHz.

Now, we can add on the figure the latitude ranges explored for Jupiter and Saturn and draw an important conclusion. The main component of UKR, the smooth broadband emission received from the night side, is only observed when the spacecraft is at high latitudes. These are regions which have not been visited by Voyager nor observed with ground based instruments for Jupiter: if this planet has an emission similar to Uranus' smooth emission, it would be unknown for us. Hence we cannot compare DAM with the main component of UKR. The only component we can compare is the broadband bursty emission of UKR, which is observed when the spacecraft is at low magnetic latitudes. Unhappily this component has not been much studied so far from the PRA data.

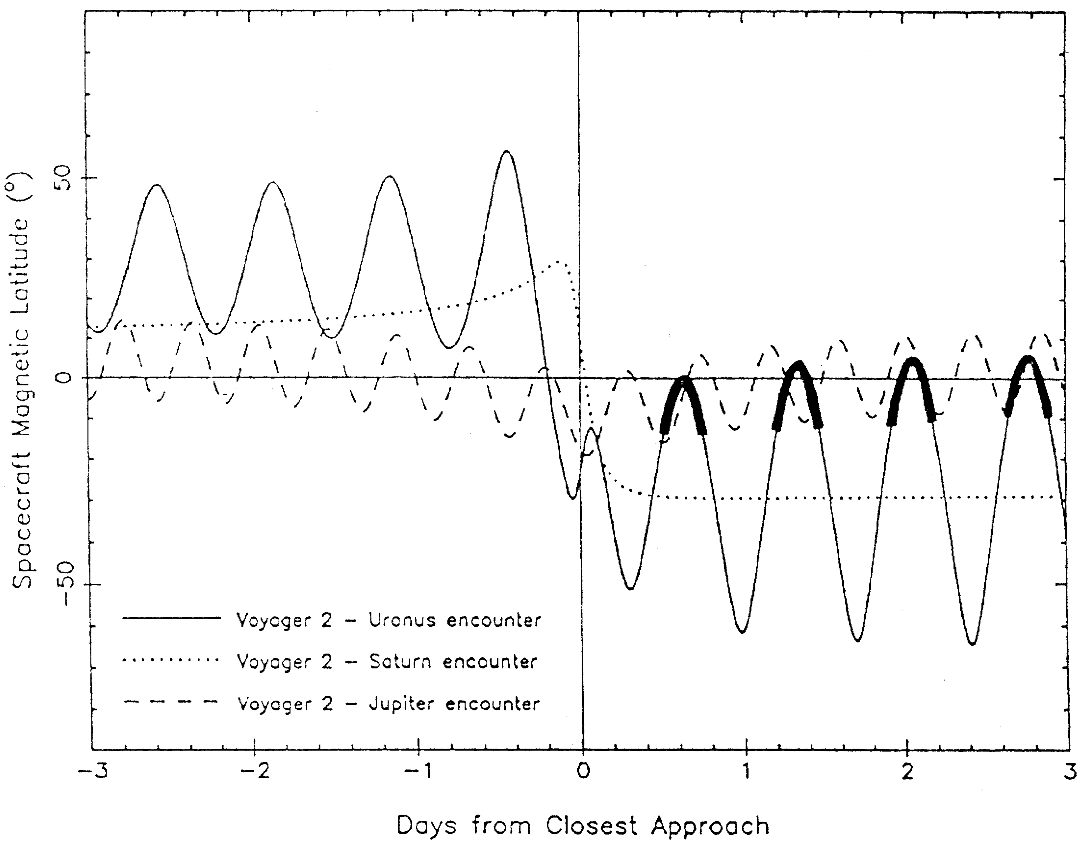

Fig. 3: Position of Voyager 2 in magnetic latitude during the planetary closest approaches of Jupiter, Saturn and Uranus. The heavy lines on the Uranus curve correspond to the emission of the night side bursty component.

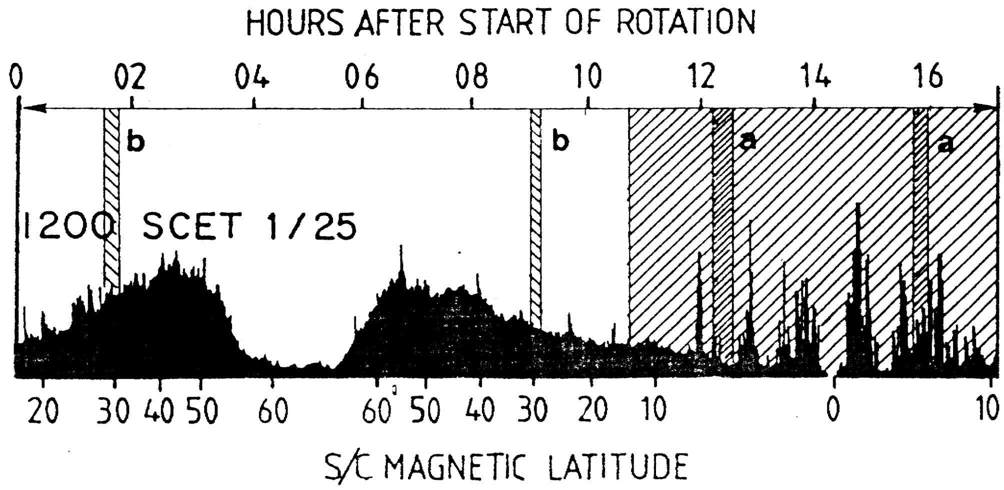

Fig. 4: Auroral emission from Uranus at 480 kHz during one rotation of the planet beginning 1986, Jan. 25 at 12:00 SCET. The lower scale indicates the magnetic latitude of the S/C. Also shown are the magnetic latitude ranges covered by the observations of Jupiter and, for Saturn, by V1 during pre–encounter (a) and post–encounter (b).

Another conclusion is that, if Saturn behaves like Uranus, the inbound and outbound V1 observations could well refer to different components of the emission. This has to be kept in mind when interpreting the Saturn Voyager data.

Another example can be taken from the AKR. If the Earth behaves like Uranus, the emission component we observed with low latitude remote spacecraft like Voyager or ISEE 3 is not the same as the one we observed at high latitudes when satellites are over the auroral zones. Again, we must be careful in interpreting the observations.

We must also note that, even if the observation coverage for the Earth is much better than for the other planets, it is often made with low altitude satellites. Hence the viewing geometry is again very different than for Jupiter, Saturn and Uranus (except during Voyager close encounters with the planets) with the result that the comparison will be sometimes difficult. An example concerns the emission modulation by the planetary rotations, which is outstanding in the observations of the outer planets, while the 24h modulation of the AKR has not been well studied so far, except from the few days of observation by Voyager 1 and 2 (Kaiser et al., 1984).

If we are interested in the actual source of emission and in the emission mechanism, a third difficulty appears: what we observe is the real characteristics of the source modified by the propagation of the waves close to the source and through other parts of the planetary environment. This effect could be very important, because the emission is generated at a frequency close to a resonant frequency of the source plasma, where the refractive index differs much from unity, and because the other magnetospheric plasmas (plasmasphere, plasmadisc, plasma tori, etc.) have resonant frequencies not far below the emitted frequencies.

This is certainly crucial in interpreting the observed diagram of emission determined from observations made far from the planets. Figure 5 shows an example of what can happen with the propagation of AKR close to the Earth: the waves will be refracted in the plasmasphere and this will change the apparent diagram of emission. Moreover, the characteristics of the emission as observed at low altitudes and from large distances will be different.

Another example of this propagation effect is seen on Figure 6: it is a change of polarization of the Jovian DAM emission when it crosses the Io plasma torus nearly perpendicular to the magnetic field. Such effect is seen only when the observer is close to the planet.

In conclusion, we must be careful when comparing the characteristics of the planetary auroral emissions from the limited amount of observations we have. It is clear that more observations are needed, especially to complete the geometrical coverage of the outer planets, and to have more remote observations of the AKR.

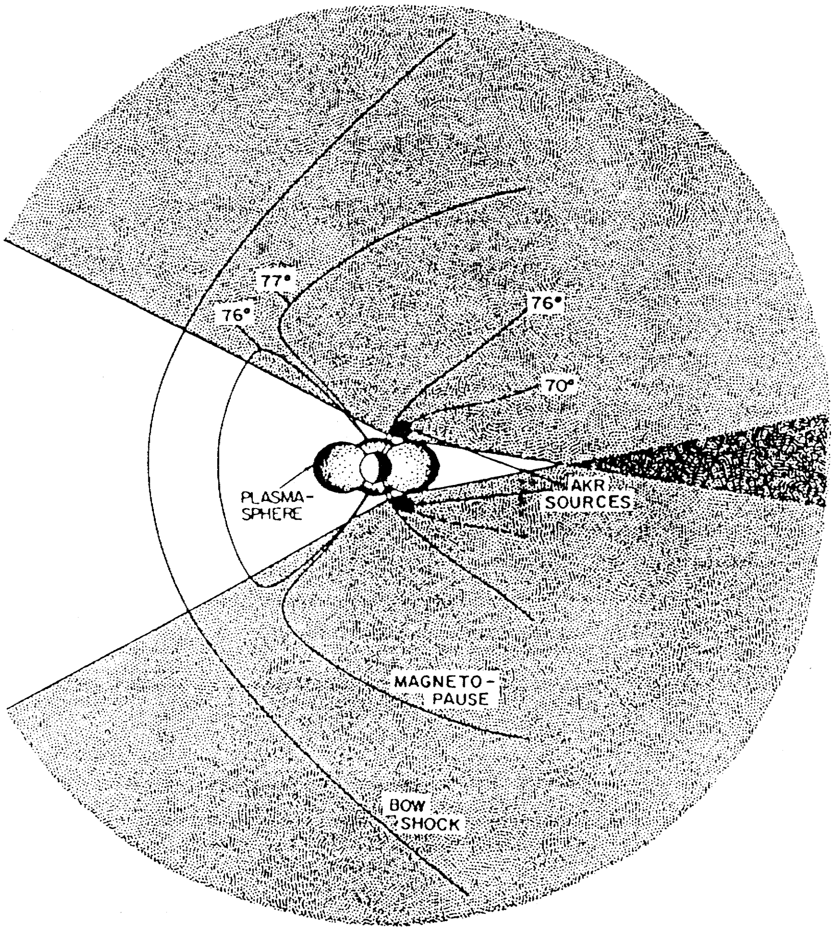

Fig. 5: Propagation of the AKR emission close to the Earth, with the effect of the plasmasphere (from Gallagher and Gurnett, 1979).

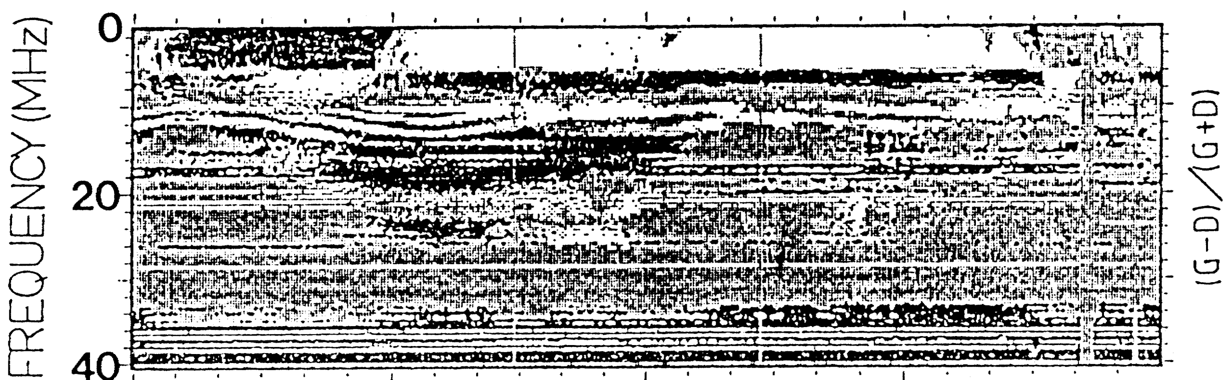

Fig. 6: Polarization fringes observed by Voyager when it was close to the planet. These fringes are likely due to mode coupling when the waves propagate through the Io plasma torus in a region quasi–perpendicular to the magnetic lines of force.

3. Relevant planetary characteristics

Before turning to the radio emissions it is useful to summarize the physical characteristics of the planets which are important in the generation and propagation of the radio waves, essentially three of them; the magnetic field, the ambient (cold) plasma in and around the source and the energetic particle population (hot plasma).

3.1 The magnetic field

To a first approximation, the magnetic field distribution at large distances from the planets corresponds to that of a dipole, not necessarily coincident with the rotation axis. Moreover the dipole can be off–set from the center of the planet and/or higher order terms, decreasing rapidly with altitude, can exist, which lead to magnetic anomalies close to the surface and distort the dipolar field.

Except for the Earth, these high order terms are not accurately known, because most of our informations on the magnetic fields come from observations made at several planetary radii.

For instance, a magnetic anomaly is often suggested to explain the modulation of SKR by the planetary rotation. Even for Jupiter, the distribution of the magnetic field on the surface differs slightly between the different models proposed (04, P 11, OTD, etc.) especially in the southern hemisphere. Strong differences appear also between the OTD model first used for Uranus (Ness et al., 1986) and the recently proposed new Q3 model (Connerney et al., 1987).

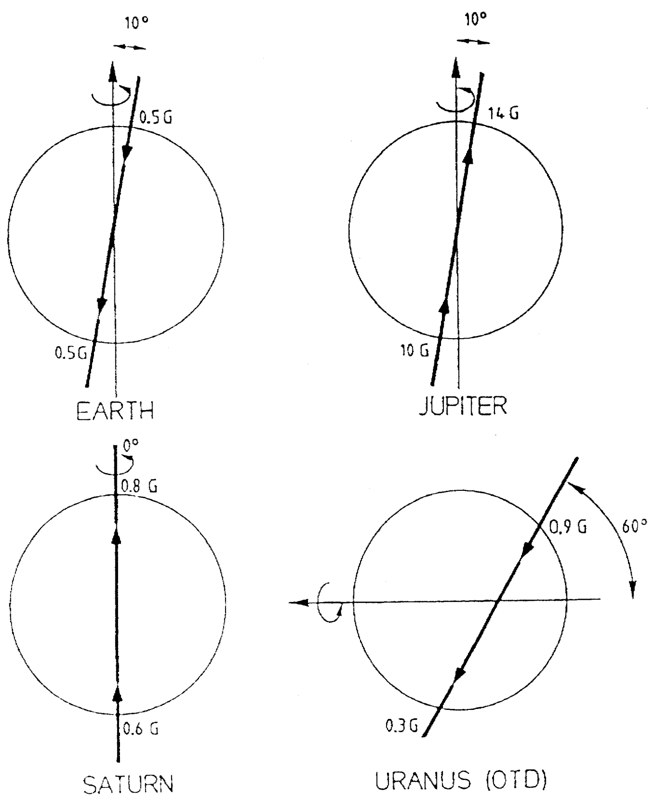

Fig. 7: The magnetic field of the four planets with the maximum field intensity observed in each hemisphere.

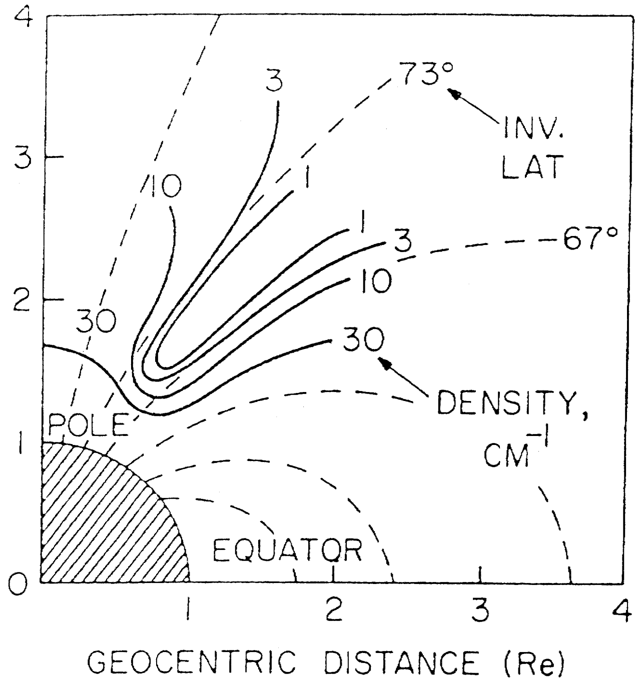

Fig. 8: The density depletion observed by ISIS in the vicinity of an AKR source (from Calvert, 1981b).

The three main characteristics of a planetary dipole field are its intensity, the tilt of its axis on the rotation axis and the sense of the dipole. These characteristics are summarized on Figure 7 for the four planets.

Three points must be emphasized:

- The magnetic field intensity close to the surface is more than one order of magnitude larger for Jupiter than for the other three planets.
- Saturn is the only planet with a magnetic axis nearly coincident with the rotation axis.
- The tilt of Uranus dipole is very large ($\approx 60°$). This, added to the fact that the rotation axis at the time of V2 encounter was approximately directed toward the Sun, gives a special viewing geometry of the planet in magnetic coordinates, and also likely a special magnetospheric configuration.

3.2 The cold plasma

We have direct measurements of the cold plasma in and around the source of emission only for the AKR. The sources of the other planets have never been penetrated by our instruments, and we have to rely on theory, or very uncertain extrapolations to derive informations about the physical conditions inside the source.

This knowledge of the cold plasma is however of great importance for the interpretation of the radio emissions. For instance, the maser synchrotron mechanism began to be popular in explaining the AKR not only when Wu and Lee (1979) showed that it could physically work, but also when Calvert (1981b) showed that the source of AKR was actually in a region depleted of cold electrons, a condition which is necessary for the mechanism to be efficient (Figure 8). The knowledge of the ratio f_p/f_c (plasma frequency to cyclotron frequency) in the source would then be very important for the other planets, but we can only conclude from what is known now that this ratio remains probably small down to the surface of Jupiter, while it could be larger than one at low altitudes over Saturn and Uranus.

Similar conclusions can be drawn for the plasmas of the inner magnetosphere, which influence the propagation of the waves from the source to the observer: plasma spheres, plasma discs, plasma tori, which are badly known. For example, all the ray tracing in the Io plasma torus which have been made so far must be taken with caution, because they use an average distribution of the electron density whereas we know from PRA observations (Warwick et al., 1979a,b) that there is much fine structure, with strong gradients of density, where most of the refraction will take place.

3.3 The hot plasma

As for the cold plasma, little is known about the hot plasma by direct observations. Number, energy and anisotropy of energetic electrons are crucial parameters to determine the intensity of the radio emission. But we have to rely on the theory of the particle dynamics inside the magnetosphere. This is very inaccurate, particularly because very little is understood about the acceleration mechanisms and where accelerations take place.

Several mechanisms can play a role in providing energetic electrons for the radio emission: direct access of solar wind particles, acceleration by magnetic reconnection in the nose or the tail of the magnetosphere, double layers, Alfvén waves, field aligned currents, etc.... The relative importance of these processes could be different for the four planets, which can explain differences in their radio emission.

We must also understand how an anisotropy of the velocity distribution function is obtained. The "loss cone" phenomenon is well understood, but other processes certainly play a role as shown in Figure 9. This figure shows the direct measurement of the electron velocity distribution in the auroral region of the Earth during inverted V events (Omidi and Gurnett, 1984), with several places where dn/dv is positive, a necessary condition to generate radio emission. Similar results would be important to get for the other planets.

It is also worth noting, that in the case of very complex magnetic field distribution as given by the Uranus Q3 model, the trapping of the energetic electrons is not easy to calculate.

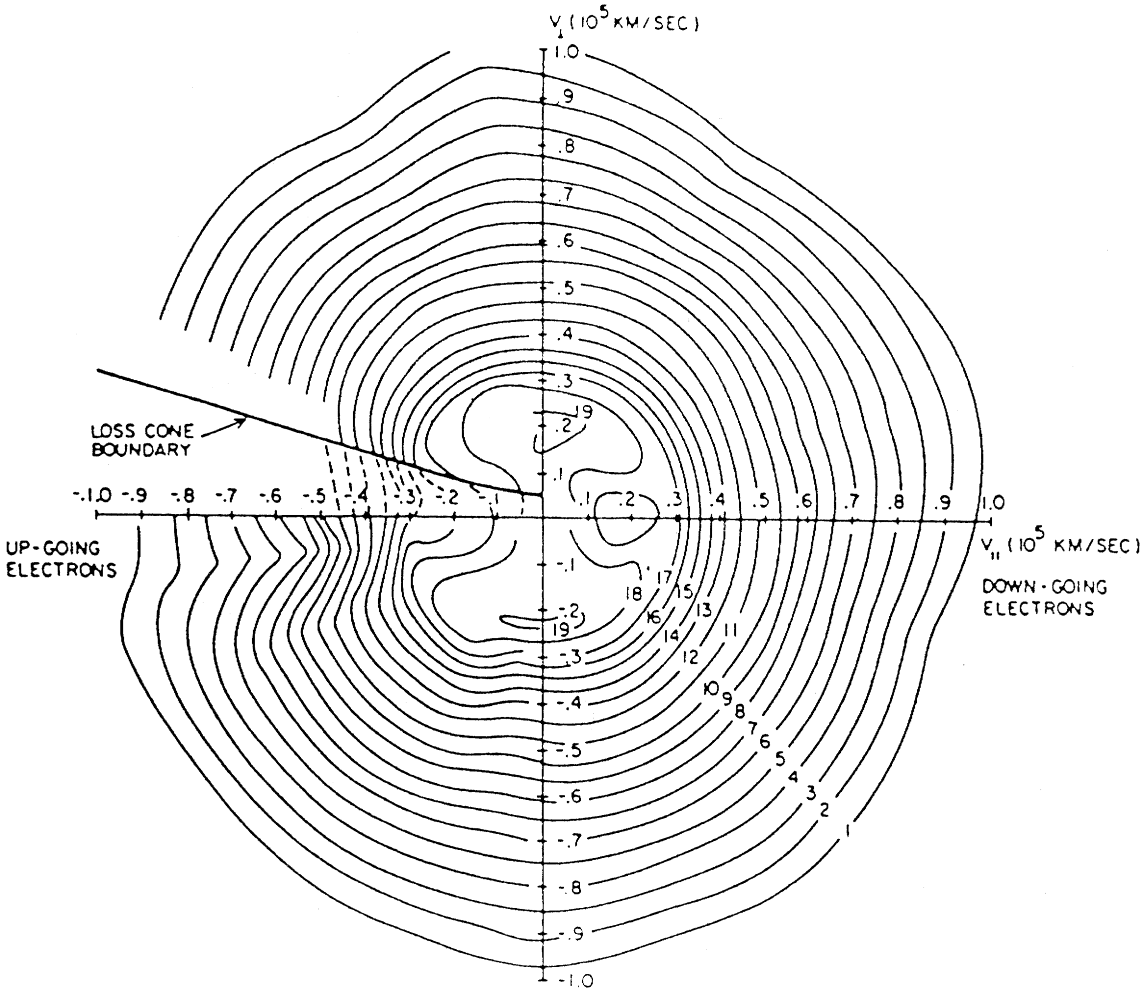

Fig. 9: Electron velocity distribution observed in auroral region during an inverted V event (from Omidi and Gurnett, 1984). The frontier of the loss cone, the hole centered on the $v_{\parallel}$ *axis and the bump centered on the* $v_{\perp}$ *axis where free energy is available are also shown.*

4. The radio emission

A general remark to begin with: The main source of plasma in the inner magnetosphere of the Earth, Saturn and Uranus is the planetary atmosphere, ionized by the solar radiation, and thus we can expect some similarities between the emissions of these three planets.

The case of Jupiter is different in that it has another very important source of plasma with the Io plasma torus. The Io plasma torus is certainly at the origin of accelerations of particles, precipitation, etc... which trigger radio emissions. This is proven by the strong control by Io on part of the DAM. The Io controlled sources have certainly no counterpart in the other planets, even if the emission mechanism is likely to be the same everywhere. On the other hand, the non Io emission, especially at frequencies lower than a few Megahertz can be compared more readily to AKR, SKR and UKR. There is also a point which must be mentioned which can certainly explain differences between the emission of Jupiter and that of the other planets. At similar distances from the planets the emitted frequency is much higher in the case of Jupiter. There the scale heights of the plasma density and of the magnetic field are much larger than the wavelength, which might lead to different efficiencies in the emission mechanism.

4.1 Frequency range and high frequency limit

In Table 1, the low frequency limits of the auroral emissions have been put into brackets, to indicate that their values are not well determined. The auroral emissions can be superposed in this range on other types of emissions such as the continuum radiation, broad and narrow band Jovian kilometric radiation, etc.... However, we do know that the low frequency auroral emissions come from relatively large distances from the planet – several planetary radii – and that their study might give information on those remote regions of the inner magnetosphere. Hence, it would be of great importance to study these low frequency limits from the PRA data.

The emissions from the four planets show a high frequency limit which is linked to the intensity of the magnetic field close to the surface of the planet at high latitudes. This supports all the theories of an emission close to the gyrofrequency.

A noticeable difference between the planets is that the high frequency limit of the Jovian DAM, which is very sharp, corresponds to the actual magnetic intensity at the cloud top (or at the ionospheric level), at least in the northern hemisphere, while it is lower by a factor of 2 or more for the other planets (a factor of 2 corresponds to an altitude of 0.25 R with a centered magnetic dipole).

Within the maser synchrotron theory, this fact can be explained by a difference in the ratio f_p/f_c at low altitudes which, as we said above, is always smaller than the one for Jupiter (the magnetic field being very strong). Hence the maser synchrotron mechanism can work down to the surface, while for the other planets f_p/f_c is probably larger so that the mechanism is limited to higher altitudes.

We can conclude that the HF limit of auroral emissions can be used to derive the maximum surface magnetic field intensity only in the case of Jupiter.

Another difference between the Earth, Saturn and Uranus on the one side and Jupiter on the other is that the observed high frequency limit is strongly modulated by the rotation of the planet only for the latter (Figure 1). This is explained by the variation of the source of the observed DAM emission in magnetic coordinates (like along the Io flux tube foot print) while it could be fixed, so that f_c = constant, for the other planets. But another possibility is that the HF limit for the first three planets is determined by a factor other than the maximum field intensity, for instance the value of f_p/f_c.

4.2 Total energy and brightness temperature

The total energy radiated by the planets in the radio domain is not accurately known. We have to compare average fluxes of very time variable sources, covering different frequency ranges. We do know that the radiated energy differs when observed from different viewing geometries but there is a large uncertainty about the actual diagram of emission. This results in a large scatter in the values published in the literature, derived from the same observational data. Table 2 gives an idea of the energy radiated by a strong burst, integrated over its frequency range and Figure 10 shows a recent determination of the spectra of AKR, SKR, and UKR peak flux densities with an average curve for Jupiter, taken over quiet as well as active periods (Gulkis and Carr, 1987).

Table 2: Total energy emitted by auroral radiation (peak amplitude, emission in a 2π ster. beam)

Earth	Jupiter	Saturn	Uranus
$3{\cdot}10^7$ W	10^{11} W	$3{\cdot}10^8$ W	$2{\cdot}10^6$ W

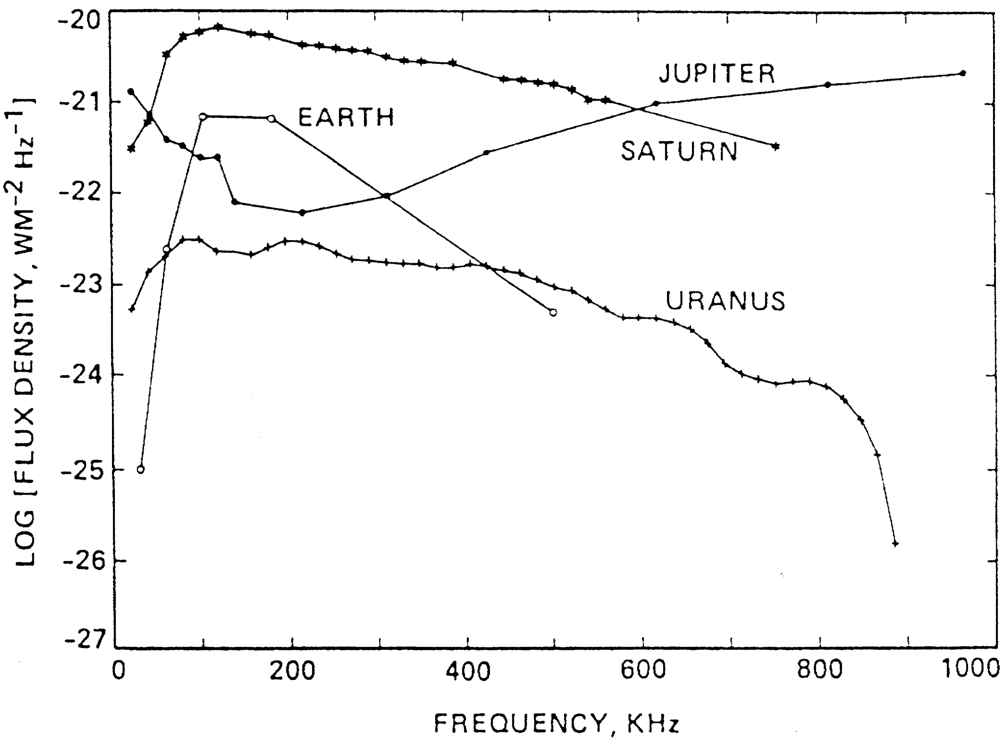

Fig. 10: Low frequency power spectra of four planets, adjusted to the distance 4 A.U. The curves for Uranus, Saturn (Carr et al., 1981), and Earth (Gurnett, 1974) are for peak flux density, while that for Jupiter (Alexander et al., 1981) is for average flux density. The Jupiter averages were taken over quiet as well as active periods; as a consequence, the Jupiter curve should be raised by about a factor of 10 when it is compared with the other curve (from Gulkis and Carr, 1987).

We can conclude from Table 2 and Figure 10 that for the Earth, Saturn and Uranus, the auroral emissions do not differ much in their energy and spectrum, but that Jupiter's is different. The small differences between the first three planets can be accounted for by differences in the source extent, or in the number and energy of the particles involved, without need for a different mechanism.

For Jupiter, the quite different spectrum reflects mainly the larger intensity of the magnetic field. The much larger total energy, by two or three orders of magnitude, is certainly partly due to the wider spectrum of the emission, which corresponds to a larger extension of the source along the magnetic lines of force. It results also likely from the presence of the Io plasma torus which leads to a more active inner magnetosphere. Here again it does not seem necessary to invoke a different emission mechanism.

A more interesting characteristic to compare would be the brightness temperatures of the sources, which is more directly related to the emission mechanism and its saturation processes. But this requires the knowledge of the source size.

We do not have any direct determination of the sizes of SKR and UKR sources.

For Jupiter, VLBI observations – only at frequencies greater than 25 MHz – give a source size smaller than 400 km (for a spatially incoherent source) (Dulk, 1970), hence a brightness temperature up to 10^{18}K, but nothing is known about the source size at lower frequencies.

For the Earth, the direct crossing of the sources by ISIS 1 (Benson, 1985) and Viking lead to a size of the same order, but with probably much finer structure, so that the brightness temperature cannot be determined with a good accuracy. It is worth noting that the interpretations of the source size for Jupiter and the Earth are somewhat different: direct in situ measurements give the real size of the AKR source, while remote VLBI observations give an apparent size which depends on its real size but also on the extension of the source in magnetic longitude and on the width of the emission diagram. It is then only an upper limit of the real source size.

4.3 Source location, emission diagram and source structure

Ground based instruments have much too poor a resolving power to allow direct localization of the sources of emission and determination of their structure. On its side, the PRA Voyager experiment has no direction finding capabilities. Therefore we have to use indirect methods, which are generally model–dependent.

We shall use in the present study the results on source location which have been published so far and generally accepted, leaving a detailed discussion of the observations to other papers.

There is an important characteristic common to the four planets: even if there is no direct determination of the source location, except for the Earth, everyone agrees that the sources of auroral emissions are at high magnetic latitudes, or more precisely on field lines reaching the planet at high latitudes. Slight differences in the source latitude of the different planets might exist, but the accuracy of the determination of source position is not good enough to give useful results.

But there are also striking differences between the observed characteristics of the sources of the different planets. The problem is to know if these differences in the apparent characteristics of the sources reflect actual differences or are due to secondary effects or to the geometry of the observations.

To compare the four planets in this respect, we shall first describe what is known about the DAM Jovian source, on which we have more informations, and then see if the observations of the other planets can fit with a source model similar to Jupiter's.

The determinations of the source structure and source location are not independent of that of the emission diagram.

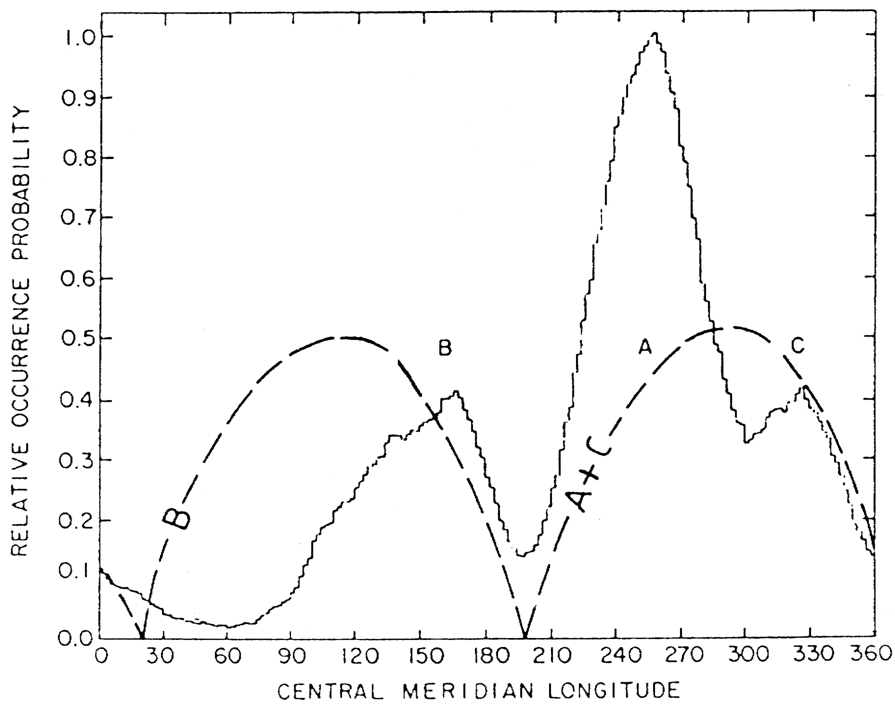

Fig. 11: Variation of the relative probability of occurrence of DAM as a function of central meridian longitude (from Thieman et al., 1988; this issue) and simplified model used in the discussion.

The main observations which put constraints on the location and structure of the DAM source in the northern hemisphere can be listed as follows:

1. The occurrence probability – and the intensity – varies with CML as shown in Figure 11. For the present study we shall use a simplified diagram with two equal sources B and A + C. The peaks are at CML 90° and 240°, the differences between sources B and A + C is likely due to high order asymmetries in the planetary characteristics, and will not be considered here.

2. The emission is at large angles to the magnetic field (or to the projection of the magnetic field on the ecliptic plane). This is deduced from statistical studies of the occurrence probability of Io controlled emission (Dulk, 1965) and from the interpretation of interplanetary scintillations (IPS) pattern (Genova and Boischot, 1981; Boischot et al., 1987).

3. The HF cut–off frequency varies with CML in a manner similar to the occurrence probability.

4. The instantaneous apparent size of the emission region is small, ≤ 400 km. This is given by VLBI measurements (Dulk, 1970) and agrees with the strong modulation by IPS.

5. Only one source corresponding either to B or to A + C is observed at frequencies higher than 20 MHz from a given CML, as we have no superposition of two arc structures and also from the non overlaping IPS patterns.

6. The instantaneous diagram of emission in the ecliptic plane is very narrow, not more than a few degrees wide, as can be concluded from the rapid decorrelation of the signals received by two receivers in a stereo–type observation (Poquérusse and Lecacheux, 1978).

7. The source of the Io controlled emission is likely not to be very different from the source of non–controlled emission. In particular, the maximum emission is observed for both sources A and B when the longitude of Io is $\approx 200°$.

These observations are generally explained by the following source model:

- The emission comes from high latitude magnetic lines of force, at a frequency close to the gyrofrequency.

- The emission is in a hollow cone centered on the line of force, with large aperture θ and narrow surface width.

- The ecliptic plane, from where all the observations have been made so far will cut this conical sheet into two beams of emission which will correspond to the two sources B and A + C.

The structure and emission diagram of the source at frequencies greater than 20 MHz can then be one of the following:

- A source with small longitudinal extension and a narrow beam width. This is incompatible with (1), because it will give only two narrow peaks in the occurrence probability CML histogram, and not the large peaks which are observed in Figure 11. This is observed only at the highest frequencies.
- A source with small longitudinal extension, but with wide beaming. This is incompatible with (4).
- A source with large extent in longitude with wide beaming. This is incompatible with (4) (the "apparent" source would be large) and (6).
- A source with large extent in longitude with narrow beaming. This is the only model which can fit all the constraints listed above.
- To account for (5) we have also to assume that the extension in longitude of the source is less than 180°; if not the two sources B and A + C would be observed from the same CML, respectively East and West of the planet.

Finally, the separation of B and A + C in CML allows to put the center of the extended source at a longitude close to 200°, which corresponds to the longitude of the tip of the magnetic dipole in the northern hemisphere.

Then we arrive to the well known model shown in Figure 12.

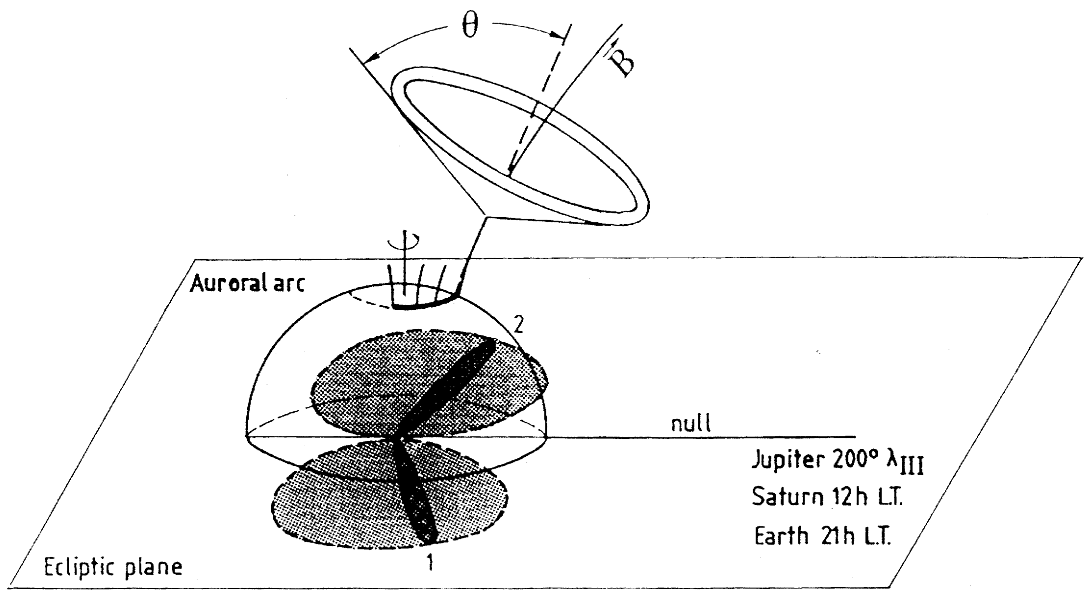

Fig. 12: Geometry of the emission along a magnetic line of force in the Northern auroral zone, and apparent diagram of emission observed from the ecliptic. The intersection of the conical emission diagram with the ecliptic plane gives two lobes 1 and 2 which correspond to sources A + C and B of the DAM emission.

Note that a magnetic field line radiates at a frequency (f) only when the gyrofrequency reaches this value. Then the limitation of the extension of the source at a given frequency is very likely determined by the size of the region where the corresponding gyrofrequency can be found. We can deduce from this, that the sources are more extended at low than at high frequencies.

It is impossible to extrapolate the discussion to low frequencies (below $\approx$ 20 MHz). First, the CML diagram is not well determined: the occurrence diagram is generally made with both RH and LH polarization, i.e. from a mixture of Northern and Southern sources. Second, we have no determination of the apparent size of the source at low frequencies. What we can say is that the model proposed for the high frequency northern source is likely valid at low frequencies with the additional possibilities that:

1. The source might cover all the auroral oval in longitude, and then two sources could be seen simultaneously, corresponding to B and A + C sources on each side of the planet.

2. The emission diagram could increase with decreasing frequency.

More studies of HOM emission are necessary to arrive at a definite conclusion.

Note that a complete discussion of the structure of DAM source of emission would include also the modulation of the observed flux due to the tilt angle of the ecliptic plane to the magnetic equatorial plane, and the observed differences between the sources B and A + C. This will not change our conclusions very much, and will not be discussed here.

In the case of SKR, it has been found that the source is at high latitude and fixed in local time near the noon meridian (Kaiser et al., 1981; Kaiser and Desch, 1982; Lecacheux and Genova, 1983).

If we assume, like in the case of Jupiter, that the emission comes from high latitude lines of force and is emitted in a narrow conical sheet of large aperture, the model will be identical to Figure 12, but the position “200° Jovian longitude” is replaced by “12:00 Saturn local time” (Figure 13). This means that if we were able to observe the emission all over the 24h local time, we would observe two beams as for the DAM. But actually we have good observations only from three small ranges of local times, which is insufficient to draw the diagram of Figure 13: i.e. the amplitude, or occurrence probability versus local time. We can only say that what we observed is compatible with a source model similar to that derived for Jupiter DAM. But other models can also fit the observations.

Note that the control of the SKR emission by the planet’s rotation is caused by a feature fixed in the planetary longitude, and not in local time, and thus it has not to be considered in the discussion of the source structure.

For Uranus the extensive exploration in magnetic latitude by Voyager 2 allows a direct determination of the beaming properties of the source on the night side.

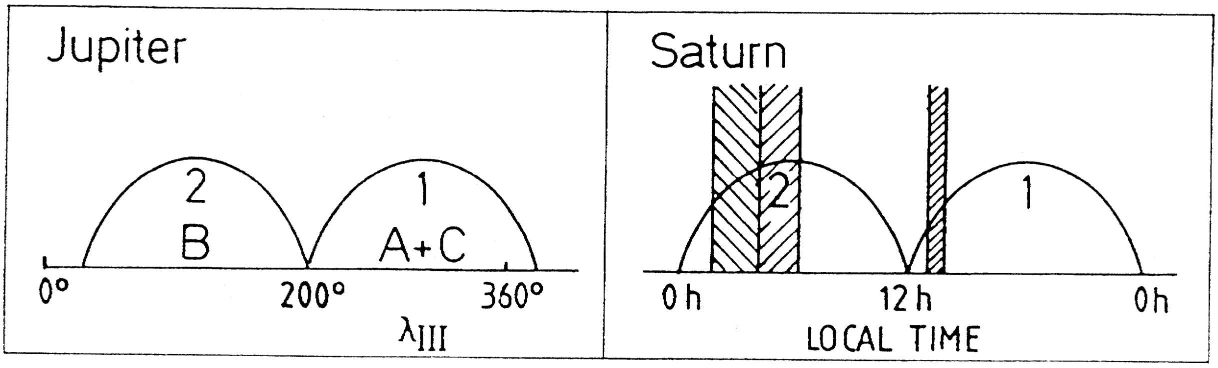

Fig. 13: Diagram of emission given by the model of Figure 12 as seen from the ecliptic plane. This diagram will be swept by the observer during each rotation for Jupiter, while we have only partial observations at three local times for Saturn.

Zarka and Lecacheux (1987) found that the observations of the continuum source fit quite well with an emission in a hollow cone centered on $\vec{B}$, with relatively large aperture (semi–apical angle $\approx 50°$). The thickness of the surface is much larger than for Jovian DAM, and increases with decreasing frequency from about 30° at 750 kHz to more than 55° at 350 kHz. The bursty component would come from the same source but at much larger angle to $\vec{B}$.

Thus the UKR source model is not different from that of DAM.

The case of AKR is not so simple, mainly because most of the observations have been made with different viewing geometries. The source is located at high magnetic latitudes and extends over a large part of the evening quadrant, as shown by the direct crossing of the source by low altitude satellites. In Figure 12 this would place a minimum of intensity around 21:00 local time when the AKR is observed from the ecliptic compared with 12:00 local time for Saturn.

But we have too few observations from the ecliptic to check this. When observed from high latitudes over the auroral zones a minimum would also appear when the observer is over the source quadrant, i.e. in the evening sector.

This is in contradiction with the observations which show a peak of emission over the source. Green and Gallagher (1985), from a careful study of AKR observations at large distances from the Earth by the IMP 6 and Hawkeye satellites, concluded that they are incompatible with a hollow cone emission. However, Calvert (1987a) tried to reconcile the data with a hollow cone by using bending of the rays close to the source; but he had to assume that the hollowness along $\vec{B}$ exists only in latitude and that the source is beamed within the magnetic meridian, which would correspond anyhow to a noticeable difference with the case of Jupiter.

In conclusion, the emission in a hollow cone centered on $\vec{B}$ is well established for the high frequency decametric Jovian emission and for UKR. It explains the observations of HOM and SKR, even if other emission models can be fitted as well. But in the case of AKR there definitively seems to be a difference in the emission diagram with the other planets. More observations are certainly needed to clear up this point. Note, however, that a possible difference in the emission diagram is not a priori a reason to reject a mechanism such as the maser–synchrotron because the propagation close to the source, in particular around the density depletion found in AKR sources, can modify significantly the emission diagram as seen from large distances.

4.4 Polarization

The planetary auroral emissions are all highly circularly polarized. The sense of polarization is generally consistent with the known direction of the magnetic field, if we assume an emission in the extraordinary mode. On a given planet, both right–hand and left–hand polarizations are observed, depending on the hemisphere – north or south – of the source.

This result is well established for the highest frequencies of the DAM Jovian emission, for Saturn and for the main source of Uranus.

However, at least two problems remain still unclear:

The first is the exact degree of polarization and the eventual existence of an O mode component. There are times when completely polarized waves have been observed, which correspond certainly to only one mode of emission. But it is not yet clear if this is always true, and if the degree of polarization does not vary with time, viewing geometry, frequency, etc.... Note that a degree of polarization differing from unity could be due to a complex source structure, to a mixture of several sources of different polarizations or to the presence of mode coupling during the propagation, and therefore is not necessarily related to the emission mechanism. But it might also reflect an emission partially on the O mode.

Actually, in the case of the Earth, where observations have been made close to the source at low altitudes, we do observe some emissions in the O and Z modes (Mellot et al., 1984; Benson 1985). But their level is much lower than that of the X mode and such an emission would be difficult to identify on the other planets. Note that these emissions in modes other than X are compatible with the maser synchrotron theory and depend on the ratio f_p/f_c in the source.

The second problem is that of the linear component, i.e. the ellipticity of the waves.

From the DAM observations made from the ground, we know that this emission has a relatively strong and stable linear component – of the order of 20 to 30 % – leading to the outstanding Faraday fringes when observed with a linear antenna (Warwick and Dulk, 1964; Parker et al., 1969). The Voyagers have only two polarization channels and cannot determine the complete state of polarization. However, for Saturn and Uranus, a careful study of the PRA data shows that the observed polarization is often explained by a 100 % circular polarization, which leaves no place for a linear component. For the AKR, the results are not clear. It seems that there is some linear component, but the result needs confirmation.

To conclude, we can say that there is very likely a noticeable difference in the ellipticity of the planetary auroral emissions.

We must note however, that the present theory of the maser synchrotron mechanism cannot predict the exact state of polarization of the emission: it depends much on the detailed amplification path inside the source. Thus the interpretation of the linear component is not yet possible, but it is evident, that the polarization contains informations on the characteristics of the source and on the degree of polarization and the ellipticity of the waves.

4.5 Fine structures on the dynamic spectra

Dynamic spectra of the auroral emissions of the four planets show many structures in time and frequency on very different scales. Some are due to external control or to the geometry of the observations, like the effect of the solar wind, the rotation of the planet or the position of the satellite Io; others have their origin in the propagation of the waves between the source and the observer: scintillation in the interplanetary medium and the Earth's ionosphere, refraction, focussion, etc...; all these phenomena are not directly related to the source of emission and will not be discussed here.

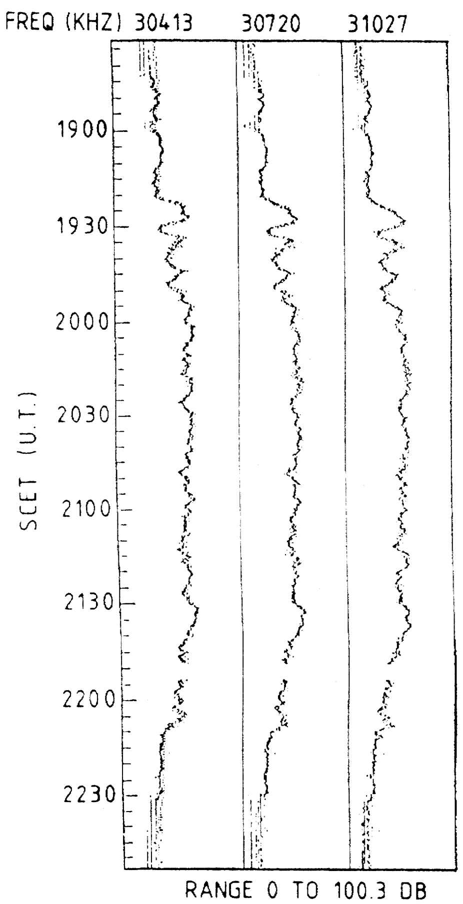

Fig. 14: Fixed frequency decameter emission observed by Voyager close to Jupiter. Note the absence of fast fine structures.

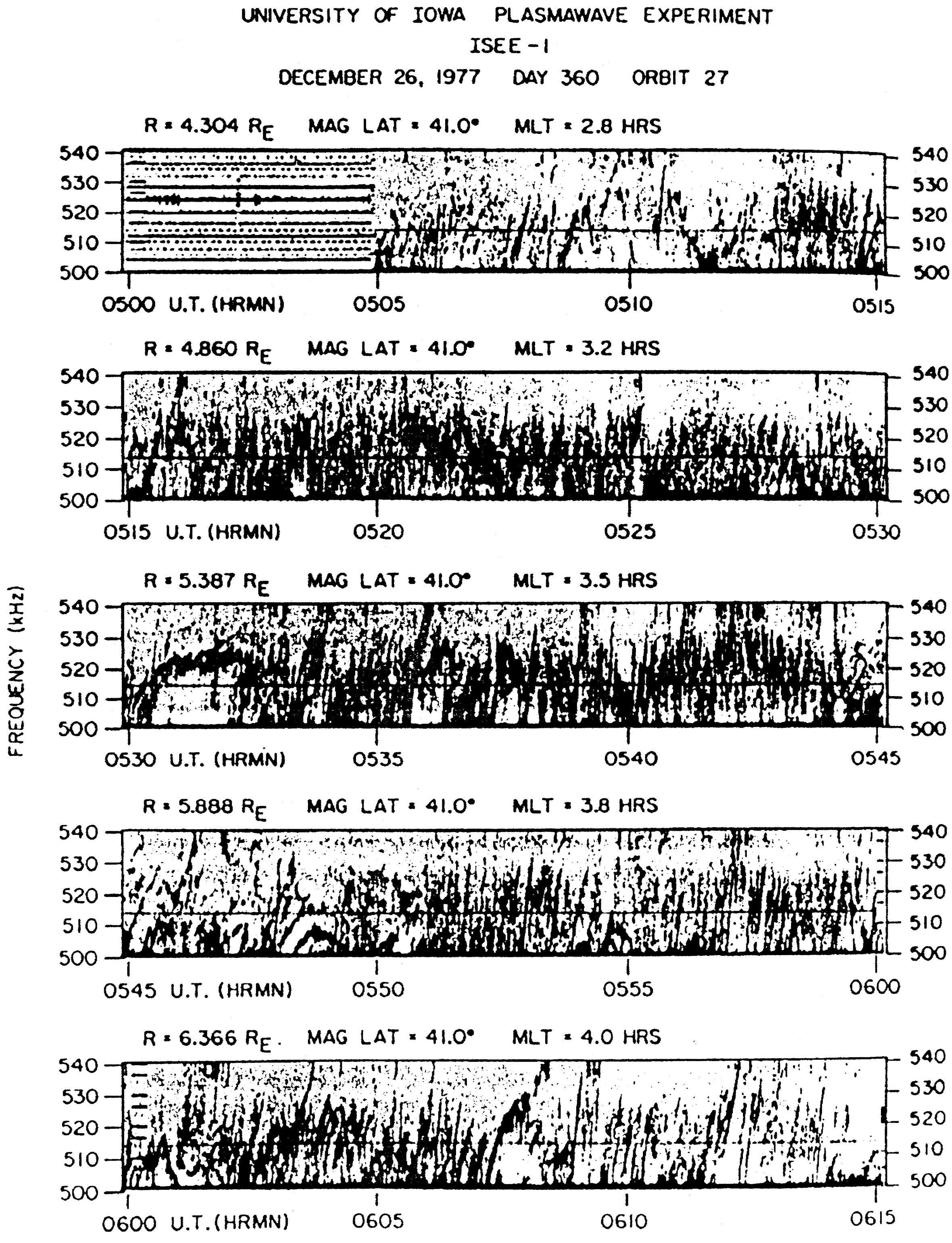

Fig. 15: Fine structure of the AKR observed by DE1 (from Gurnett et al., 1979a).

There are also other structures, generally on small time and frequency scales, which certainly have their origin in the source itself, and are intimately related to the emission mechanism and the source structure. Those fine structures are then particularly interesting to compare in the spectra of the four planets.

Because of the interplanetary and ionospheric scintillations, it is difficult to detect very fine structures in the DAM observations from the ground. But when observed by Voyager close to the planet, the emission appears generally smooth down to the 30 ms resolution of the instruments (Figure 14). The main intensity variations are the well known arc structure, with time scales of several minutes (Warwick et al., 1979a,b), but the theories proposed so far – Alfvén wings (Gurnett and Goertz, 1981) or refraction in plasma structures (Lecacheux et al., 1981) are not directly related to the emission mechanism. There are also the so called modulation lanes, the origin of which is still completely unknown (Carr and Desch, 1976).

Very few results have been published so far on the fine structures of the Jovian HOM dynamic spectra, even though we know that fine structures exist. An example is the quasi periodic peaks observed in the fixed frequency data at a 30 ms resolution (Warwick et al., 1979a,b) and the structure presented by Thieman et al. (1988, this issue). It is very important to study these structures in more detail to allow a good comparison with what we know about the AKR.

The AKR emission is completely dominated by fast and narrow band fine structures (Gurnett et al., 1979a) which, at least on published examples, drift mainly from low to high frequencies (Figure 15). Recently, Calvert (1987a) showed that even much finer structures can exist, with bandwidth down to only a few Hertz. This result is very important for its impact on the emission mechanism and the source size, and it would be very interesting to search for similar structures, in the dynamic spectra of the other planets.

The SKR seems intermediate between DAM and AKR, with sometimes a smooth emission on a time scale of a few seconds, sometimes more rapidly variable.

UKR, at least the main night side component, is probably the most continuous emission, very smooth on time scales of tens of minutes (Figure 1 and Figure 4 of Leblanc et al., 1987). The only noticeable features are fast and narrow band quasiperiodic bursts sometimes superimposed on the continuum, for which we have no explanation so far (Warwick et al., 1986). This main night side component is seen when the observer is over high magnetic latitudes. But it is also known that, when the observer is at low latitudes, a second component is observed, much more variable, on time scales faster than 6 s, which seems to come from the same source. The relation between these two components is not yet clear, but the possibility that they correspond to different emission mechanisms cannot be excluded.

We can conclude that there are noticeable differences between the fine structures of the dynamic spectra of the four planets. But, as for the polarization, the emission mechanism theories, in particular of the maser synchrotron process, presently cannot predict those fine structures and relate them to the physical conditions inside the source.

Anyhow, it is clear that special efforts are needed in this field, in order to give clues to the details of the emission mechanism, to the fine structure of the source and to the acceleration and precipitation processes of the high energy electrons.

To be complete, we have to mention the millisecond bursts, which are observed in the Jovian DAM emission and have very special and well defined characteristics. They are not explained yet, and have no counterpart in the other planets' emissions. One of their characteristics is that their occurrence is strongly controlled by the position of Io; this could be a reason why they are observed only in Jupiter emissions.

4.6 Modulation by the planetary rotation

Another characteristics of the auroral emissions which is interesting to compare between the four planets is the intensity modulation of the observed emission at the period of the planetary rotation. This modulation is very clear for Jupiter, Saturn and Uranus, and has been used to determine the period of rotation of the planets. The 24h periodicity of the AKR has been detected only from the limited amount of data obtained near the ecliptic plane by the Voyagers just after launch (Kaiser et al., 1978), and has not been studied in detail so far.

For Jupiter and Uranus, the source – or sources – of emission are fixed relative to the surface of the planet, and their emission is beamed in both magnetic longitude and latitude. During the planetary rotation, the beam will sweep by the observer so that the observed intensity will vary like with a rotating search light. As the rotation axis is tilted on the dipole axis, to which the beam is fixed, the modulation is due to the beaming in both longitude and latitude.

For the Earth the source is fixed in local time. Thus, the modulation cannot be due to a search light rotating with the planet. But since the source is also fixed in magnetic latitude, the tilt between the rotation and magnetic axis will lead to a periodic change of the source position relative to the observer which can explain the intensity modulation if the emission is beamed in magnetic latitude. The absence of a 24h periodicity in the visible auroral activity, to which the radio emission is well correlated, leads to the conclusion that there is no intrinsic modulation of the source intensity by the planetary rotation and that the observed modulation is only a result of the changing viewing geometry.

The case of Saturn is quite different. A clear periodicity has been observed in the SKR intensity, but it can be explained neither by a rotating search light, because the source is fixed in local time like AKR, nor by the wobbling of the source in rotational latitude because rotational and magnetic axis are aligned. Thus, we have to find a different explanation for Saturn.

The source being fixed in local time, the variations must be due to some feature fixed relative to the planet and rotating with it in front of the observer. This feature would be able to trigger, or at least to modulate the intensity of the emission of the source fixed in local time.

A magnetic anomaly, undetected by Pioneer 11 or the Voyagers, has been proposed. But then a variation of the high frequency limit of the emission would be expected as in the case of Jupiter. If this limit was due to a threshold of f_p/f_c, as in the maser synchrotron process, the constancy of this limit with rotation would mean that f_p varies in the same way as the magnetic field intensity.

5. Conclusion

To conclude, we can state that the behavior of the four planets is similar, at least to a first approximation. This is based mainly on the total radiated power, the high degree of circular polarization and its sense which is related to the direction of the magnetic field, and also from the fact that the source lies at high magnetic latitudes, i.e. in regions where high energy electrons are able to precipitate. This conclusion justifies the search for a common mechanism of wave–particle interaction to explain all the auroral emissions.

On the other hand, one must not ignore the differences between the planets. Among these differences, the most relevant to the emission mechanism are the emission diagram, the amount of linear polarization, the fine structures in the dynamic spectra and the relation between the high frequency limit of the emission and the magnetic field intensity at the surface.

Also, the difference in the control by the solar wind and, most important, the difference between the location of the sources – fixed relative to the planet for Jupiter and Uranus, fixed in local time for Saturn and the Earth – are very interesting. They can help to determine where the electrons are accelerated and, more generally, to study the particles dynamics in the inner magnetosphere.

The study of differences between the four planets – waiting for the detection of Neptune – is probably the most exciting part of the study of the planetary auroral emission.